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Sound propagation loss prediction for 100 Hz receiver

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SOUND PROPAGATION
LOSS PREDICTION FOR 100 Hz RECEIVER

by

Walter Lewis Glenn, Jr.

UNITED STATES
NAVAL POSTGRADUATE SCHOOL

THESIS

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Lieutenant, United States Navy
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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

This paper reports an attempt to simplify for ease in field use
the complex numerical model for sound propagation loss prediction
developed by Dr. C. S. Clay, Captain P. M. Wolff, and Dr. P. R. Tatro
(LCDR, USN). Due to time required for communications and computa-
tion, the present results of this model are not available for imme-
diate use by the operator in the field.

This computerized model was used to analyze propagation loss for
temperature profiles with sea surface temperature varying between 10C
and 25C and variation in mixed layer depth from the surface to 300
meters. From these data formulas and graphs were developed to predict
convergence zone range, width, and intensity and the 100-decibel propa-
gation loss range. These results are intended for operational use by
field personnel.

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CHAPTER I

INTRODUCTION

A numerical model for calculating sound propagation loss from a source at a given depth to a receiver at a given depth in the sea is presently employed at the Fleet Numerical Weather Facility, (FNWF), Monterey, California. This model is used to provide tactical information to operational naval forces and for other strategic uses. However, due to turnaround time required for computation and communications, the results are not available for immediate operational usage in the field.

This model was developed and adapted for computers in November 1967 by C. S. Clay, P. M. Wolff, and P. R. Tatro. Recent comparisons of predicted values with values obtained in controlled field studies have shown the model to produce excellent results. The Bolt, Beranek, and Newman (1966) report gave finer detail on sound loss, but the FNWF model compared very favorably over the entire sound propagation loss path.

Having worked operationally in this field as ASW officer on the USS VESOLE (DDR-878) and on the USS RICHARD E. BYRD (DDG-23), the author has firsthand experience in the many frustrations encountered in coping with sound detection in the sea. This frustration is shared by other operators as noted by Glennon (1965). By using the results of the FNWF model as a standard, it is intended to develope some simple equations and graphical displays for use by the operator directly in the field.

This work is concentrated on the convergence zone range, width, and intensity for convergence zones one, two, and three. Data and graphs

are also presented for the 100-decibel propagation loss range. Additional runs would be required to utilize the 100-decibel data in a more meaningful manner.

This paper is divided into three principal parts. The first part is an explanation of the basic features of the sound propagation loss model used to develop the data. Since the model description has not been published, this information is derived from personal consultation with Dr. P. R. Tatro and Dr. C. S. Clay.

The second part will include an approach to obtaining data for reduction, and a description of the methods used for reducing the data obtained. The fine atlas of Pacific water conditions developed by Muromtsev (1963) has been of considerable help in developing this ocean model.

The last section will be the display of graphical results and the equations developed for operational use. These calculations will be shown with the realization that some differences may exist between these results and actual conditions in the field. It is intended that the model predictions will be accurate enough to be of some operational use.

CHAPTER II

SOUND PROPAGATION LOSS MODEL

The sound propagation loss model was developed to calculate the
transmission loss for low frequency sound in the world oceans. Losses
developed in the model depend on sound velocity profile, depth, sea
state, sound frequency, and the type of ocean bottom present. These
parameters in turn are dependent on such variables as sea surface
temperature, mixed layer depth, temperature profile, source and re-
ceiver depths, bottom roughness, and salinity. The model was developed
in such a manner that these variables may be changed independently as
demanded by environmental conditions or operational need. Anderson
and Lesser (1959) indicate some effects of these changes.

The procedures in the construction of this model have been used for
experimental analysis by various research facilities. The model com-
bines these procedures with modern high speed computers to provide
products for sonar systems on a worldwide scale.

Sound loss in the model is assumed to occur over ten different
types of paths in the ocean. These paths are:

(1) First bottom bounce path up

(2) First bottom bounce path down

(3) Second bottom bounce path up

(4) Second bottom bounce path down

(5) Convergence zone path up

(6) Convergence zone path down

(7) Direct path up

(8) Direct path down

(9) Surface duct path

(10) Subsurface duct path.

Urick (1964) and Anderson and Pedersen (1965) have further amp-
lifying details on these transmission paths in the ocean.

For further clarification of these paths, a graphical display of
each path is shown in Figures 1, 2, 3, and 4.

Sound energy is traced along ray paths for every two degrees
from horizontal (0 degrees) to nearly vertical (88 degrees). Sound
propagation loss is computed and stored in the computer at 1000 yard
(0.5 nautical mile) increments for ranges extending from 1000 yards
to 250,000 yards. Since these are one-way transmission losses, they
should be doubled if used with active sonar systems.

Sound energy loss contributions to the total energy loss along
the various paths are calculated separately: the total loss is the
ratio of total energy available via the various paths to an initial
energy assumed to be unity. This is conventionally expressed as a
logarithmic unit, the decibel. These components are independent of
each other and the method for obtaining each component will be covered
in the following paragraphs.

Losses Along Direct Path, Convergence Zone and Bottom Reflected Paths

Losses via direct path, convergence zone, and bottom bounce are
calculated by use of the following equation:

$$\text{Loss} = 10 \log \left(\frac{R}{\cos \theta_i}\right) + 10 \log L + aR + N_b + N_s \tag{1}$$

where

R = range from source to receiver

θ_i = angle of ray leaving source

Figure 1

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CONVERGENCE ZONE PATHS

Figure 2

Figure 3

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SURFACE AND SUBSURFACE DUCT PATHS

Figure 4

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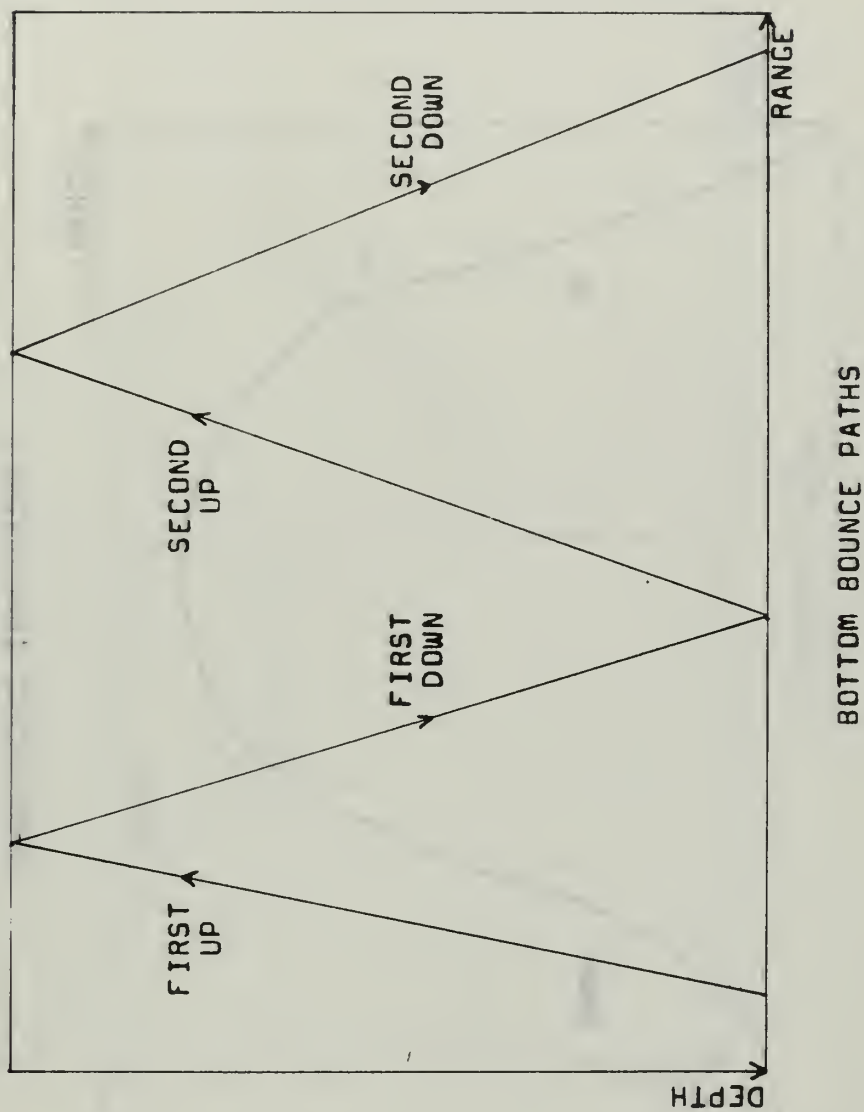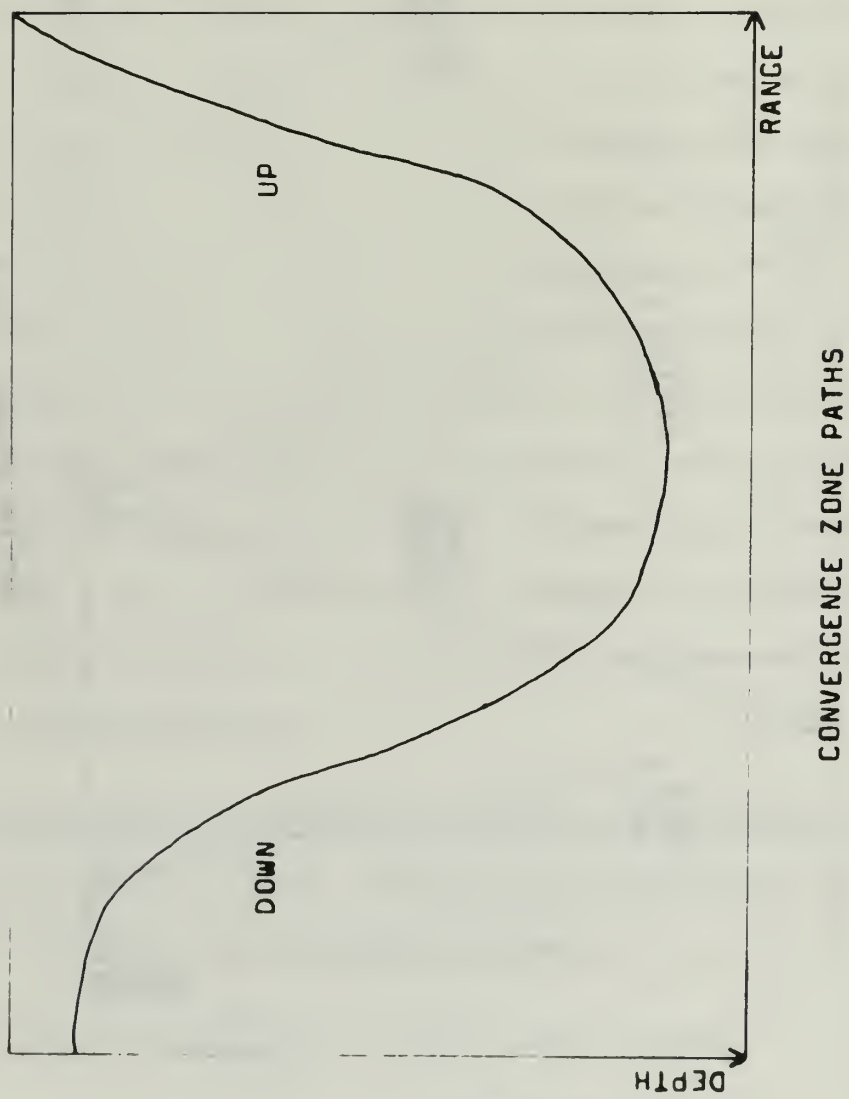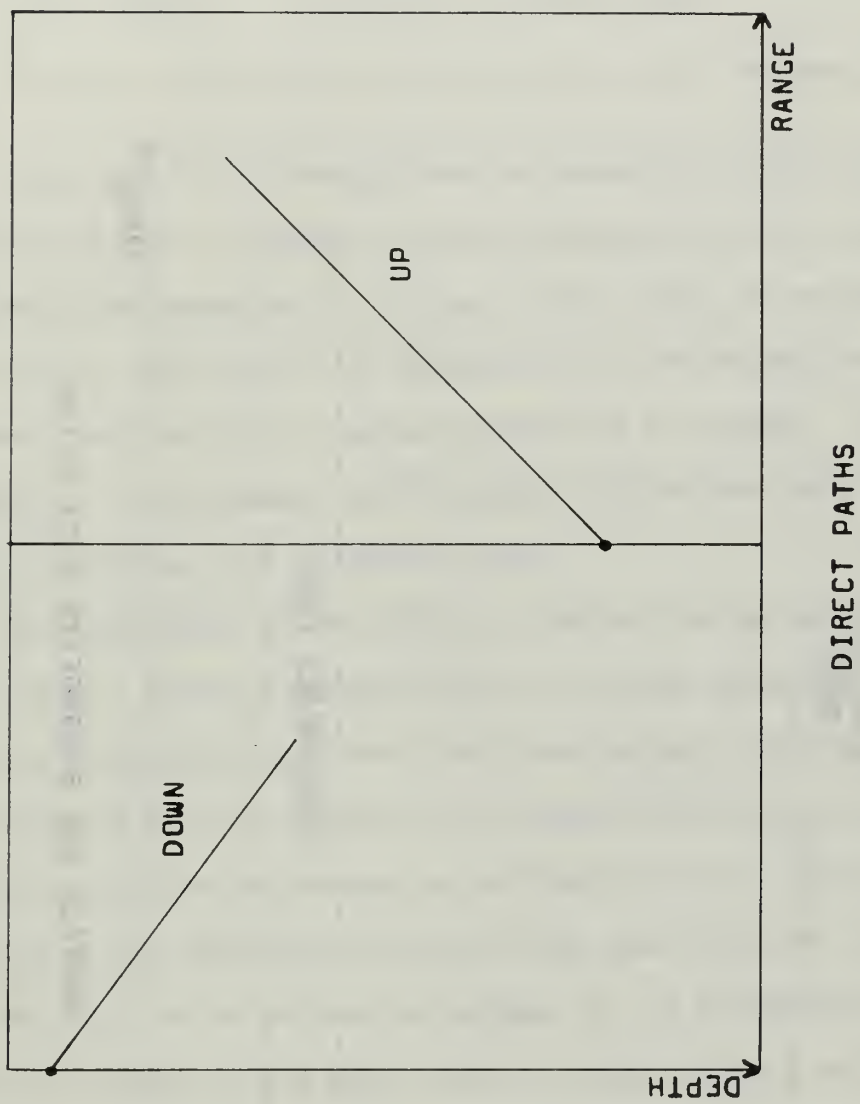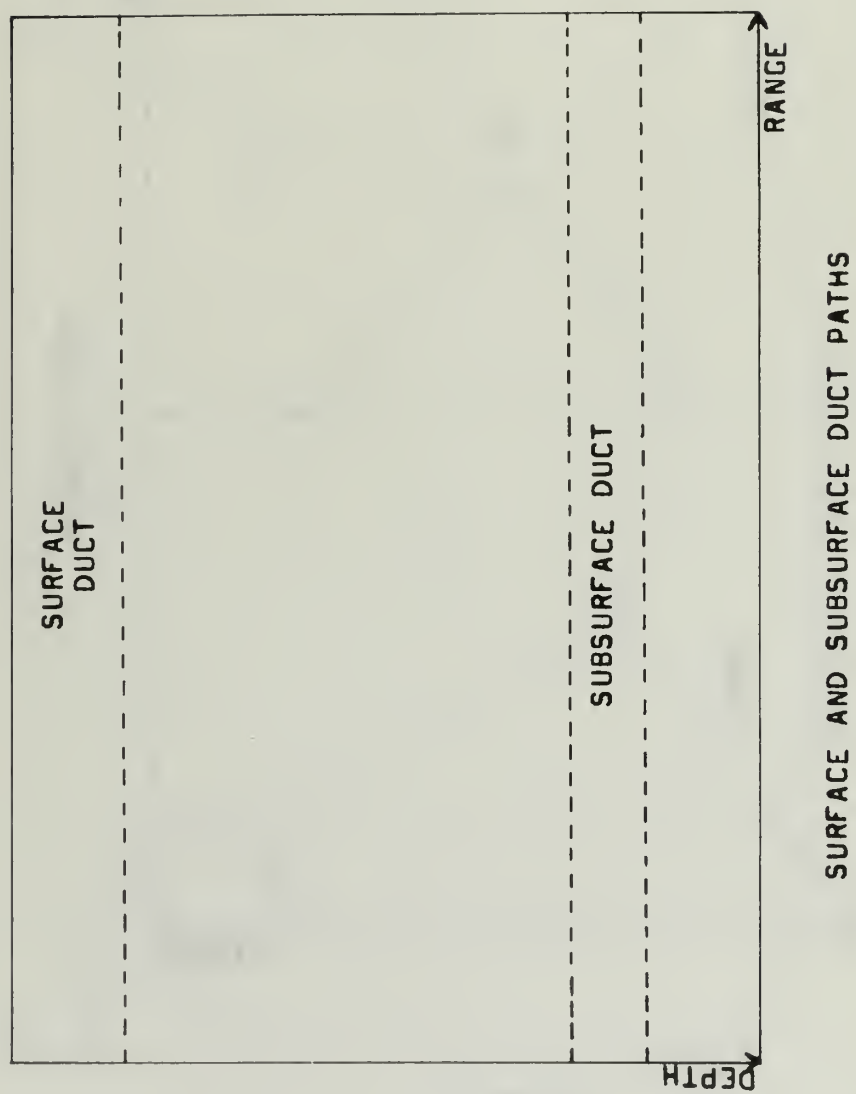
L = vertical distance between spreading rays in the range-
    depth plane

a = absorption coefficient

N_b = loss due to reflection from bottom

N_s = loss due to reflection from ocean surface

$10 \log \left(\dfrac{R}{\cos \Theta_i} \right)$ = cylindrical spreading loss

$10 \log L$ = differential spreading loss in the range-depth plane.

Since most of the ocean bottom is considered rough for low fre-
quency sound, this roughness has been accounted for in the model by
the term N_b in equation (1). Using a varied scale of roughness from
one to five, where one is the smoothest type bottom and five the
roughest, the loss due to bottom variability is computed. The cal-
culation of the roughness has been made using seismic date, physio-
graphic provinces, and bathymetric data.

The composition of the bottom is included in the model through
N_b by using a given propagation loss for certain materials. At present
only two designations are used, and these factors differentiate between
the "fast" or low loss bottom of the Atlantic Ocean and the "slow" or
higher loss bottom encountered in the Pacific Ocean. N_b is also a
function of the angle which the sound ray makes with the ocean bottom.

The loss due to surface reflection, N_s, is a function of sea
state, the angle the ray makes with the ocean surface, and the fre-
quency of the sound traveling through the water. The cylindrical
spreading loss and the differential spreading loss combine to give the
geometric spreading loss of the signal.

Bottom reflected energy is calculated using equation (1) out
through only two bottom bounces. Energy loss after the second bounce
is extrapolated using:

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$$\text{LOSS} = \text{Constant} + 10 \log R + aR + AB \cdot R \tag{2}$$

$$\text{Constant} = L - (10 \log R_1 + aR_1)$$

L = sound energy at end of second bottom bounce

R_1 = range to end of second bottom bounce zone

R = total range

$$AB = \frac{L_{0.4}}{D_c}$$

$L_{0.4}$ = energy loss at $\theta_b = 0.4$ radians

θ_b = angle incident ray makes with bottom

D_c = range where no more rays exist that have hit the bottom only once, or twice for first or second bottom bounce respectively.

Surface Duct and Subsurface Duct Losses

Surface duct and subsurface duct losses are treated using an approximation to a normal mode solution. The equation used for this determination is

$$\frac{I}{I_o} = \frac{N\Delta\theta}{RZ_o} e^{-\beta \frac{\sqrt{x_o \gamma}}{Z_o} R} e^{-aR} \tag{3}$$

$$\text{Loss} = -10 \log \frac{I}{I_o}$$

where

R = range from source to receiver

I_o = initial intensity of signal

$\Delta\theta$ = angle of energy trapped in a duct of depth Z

x_o = half cycle distance

γ = wavelength of sound

α = absorption coefficient

Z_o = the vertical extent of either the surface or the sub-
surface duct

β and N = empirical constants.

β and N may be altered as verification data from field studies become available, which permits the model to be "tuned" without diffi-
culty.

CHAPTER III

FIELD PREDICTION APPROACH

With this model available for sound loss prediction, the problem
was to determine the variables to be used to produce information satis-
factory for field prediction. James (1966) and Urick (1967) offer
guidance in determining the best group of variables.

The parameters available included sea surface temperature, mixed
layer depth, temperature gradient, sea state, source depth, receiver
depth, frequency, bottom depth, bottom type and roughness, and salinity.
Each parameter may be varied independently to determine the effects it
has on the total propagation loss in sound transmission through the
sea, which is indicated in matrix form in Figure 6. An interpretation
of the matrix is given in Figure 5.

The sample output in Figure 6 gives the propagation loss from the
source to the receiver for a 4000-meter (13,123 feet) water depth, zero
mixed layer depth, and 15C sea surface temperature. The first, second,
and third convergence zones are underlined and can be clearly seen in
the particular example.

Sea surface temperature, mixed layer depth, and temperature
gradient have a strong influence on sound propagation and are easily
determined operationally at the scene; therefore, these variables were
selected for extensive use in this study. The selection of particular
ranges of values to be used will be discussed in detail below.

Primary interest was centered on convergence zones which are
caused by the partial focusing of refracted ray paths and generally
require a deep sound channel and large ocean depth. Thus, variation
in bottom depth over a limited range was included. The focusing

Figure 5

FAMILY 1 MLD 000 150   SOURCE AT 100 FT.   RECEIVER AT 90 FT.

DEPTH 13123 FT.   ROUGHNESS 4.   OCEAN = P.   FREQ = .10 KHZ.   SEA STATE 4.

Depth									
5.5	57.1	90.1	90.3	90.7	91.1	91.5	92.0	92.5	93.0	93.4
5.5	93.9	94.4	94.9	95.3	95.8	96.2	96.6	97.0	97.4	97.8
10.5	98.2	98.6	98.9	99.3	99.6	100.0	100.3	100.7	101.0	101.3
15.5	101.6	102.0	102.4	102.7	103.0	103.4	103.7	103.7	103.8	103.9
20.5	104.0	104.1	104.2	104.3	104.4	81.7	74.8	76.3	83.6	88.1
25.5	89.9	91.6	93.1	95.3	123.6	123.8	124.0	124.1	124.3	124.5
30.5	124.6	124.8	124.9	127.9	128.0	128.1	128.1	128.2	128.3	128.3
35.5	128.4	128.5	128.5	128.6	128.6	128.7	128.7	128.8	128.9	128.9
40.5	129.0	129.0	129.1	129.1	129.2	129.2	129.3	129.3	129.4	129.4
45.5	129.5	129.5	83.2	81.2	81.7	82.7	85.8	89.3	91.1	92.3
50.5	93.3	94.1	94.9	95.7	96.5	97.4	98.0	100.0	188.6	189.1
55.5	189.6	190.0	190.5	190.9	191.4	191.8	192.2	192.5	192.9	193.2
60.5	193.6	193.9	194.1	194.4	194.7	194.9	195.1	195.3	195.5	195.6
65.5	195.8	195.9	196.0	196.1	196.2	196.3	196.4	196.4	91.5	86.4
70.5	84.9	85.3	85.6	86.2	87.6	90.1	93.9	96.1	97.6	98.7
75.5	92.6	100.3	100.6	99.7	93.9	98.1	97.6	97.2	96.7	96.1
80.5	95.6	97.4	196.9	196.9	196.9	196.9	196.9	196.9	196.9	197.0
85.5	197.0	197.0	197.0	197.0	197.0	197.0	197.0	197.0	197.0	197.0
90.5	197.0	197.0	197.0	197.0	197.0	90.2	88.6	87.7	87.9	88.1
95.5	88.3	88.8	90.0	94.2	197.0	197.0	197.0	197.0	197.0	197.0
100.5	197.0	197.0	197.0	105.8	104.4	102.0	102.4	105.5	107.0	197.0
105.5	197.0	197.0	197.0	197.0	197.0	197.0	197.0	197.0	197.0	197.0
110.5	197.0	197.0	197.0	197.0	197.0	197.0	197.0	197.0	197.0	197.0
115.5	197.0	197.0	197.0	197.0	89.8	89.8	89.7	89.7	89.6	89.8
120.5	91.0	95.7	91.8	90.3	197.0	197.0	197.0	197.0	197.0	197.0

Figure 6

effect can give an intensity from 10 to 10^3 times the intensity without this focusing effect.

Source depths, receiver depths, and sound frequencies were determined through operational considerations. Source depths of 20 feet, 60 feet, and mixed layer depth plus 100 feet; and receiver depths of 20 feet, 90 feet, and 300 feet were used. Frequencies used were 100 Hz, 3.5 kHz, and 10.0 kHz.

Sea state was evaluated for states two, four, and six, while salinity was assumed constant at 34.70‰. This value was chosen since it is the average surface salinity for the Pacific Ocean according to Muromtsev (1963).

The study was confined to the Pacific Ocean and a "slow" or "P" bottom type was used. The bottom roughness coefficient used was four, since that type bottom occurs most frequently in the Pacific Ocean. A bottom depth of 4000 meters was chosen since this approximates the depth of much of the water close to the western coast of the United States. Data were also obtained for depths of 5000 meters and 6000 meters; however, these data were not as extensive as those obtained for 4000 meters.

Mixed layer depths were varied between the surface and 300 meters in 100-meter increments. Sea surface temperature was varied between 10C and 25C. This range of values was chosen as representative of most of the Pacific Ocean. Data from Muromtsev (1963) and from personnel working extensively with the Pacific Ocean at the FNWF were used to determine the initial temperature profiles. Since most of the extreme variation in water temperature is observed to occur in the upper 400 meters of the ocean, this layer was used in the model for

strong temperature gradient variations. Sea surface temperatures were divided into three groups or families. These groups were 10 to 15C, 15 to 20C, and 20 to 25C.

To establish the initial temperature profile for input to the sound propagation loss model, the three families were assigned constant profiles from 400 meters to the maximum depth of the water (4000 meters, 5000 meters, or 6000 meters). Examples of each of the three families with zero mixed layer depth are shown in Figures 7 and 8, which give conditions in the upper 1000 meters, and in the entire 4000 meters, respectively. These three families represent broad generalizations of the actual conditions in much of the Pacific Ocean, necessary because of the scope of this study.

Using these three families with three temperatures from each (family 1: 10.0C, 12.5C, 15.0C; family 2: 15.0C, 17.5C, 20.0C; family 3: 20.0C, 22.5C, 25.0C) and four mixed layer depths from 0 to 300 meters in 100-meter increments, thirty-six initial programs were constructed. They were to be evaluated by the computer model using sea states two, four, and six; source depths of 20 feet, 60 feet, and mixed layer depth + 100 feet; receiver depths of 20 feet, 90 feet, and 300 feet; and frequencies of 10.0 kHz, 3.5 kHz, and 100 Hz.

This initial run produced eighty-one pages of data (sample shown on page 22) for each of the thirty-six initial inputs. Upon review of the output, it became obvious that meaningful analysis of 250 data values for 2,916 data pages would not be possible in the time available.

Operational usefulness was the main requirement in determining the limits of this study. The decision was made to pursue the 100 Hz propagation loss profile only. The source depths were reduced to
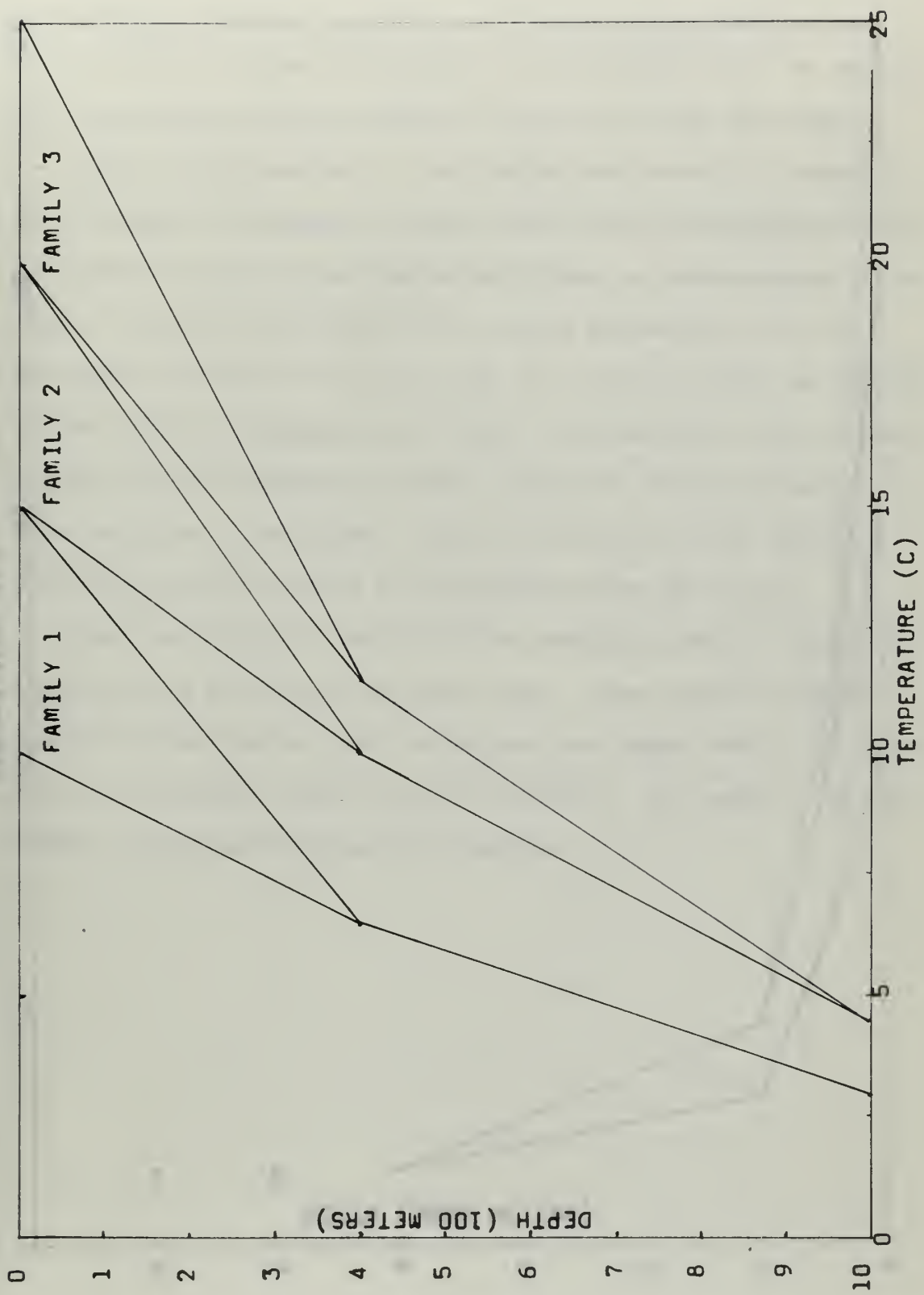
Figure 7

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Figure 8

26.
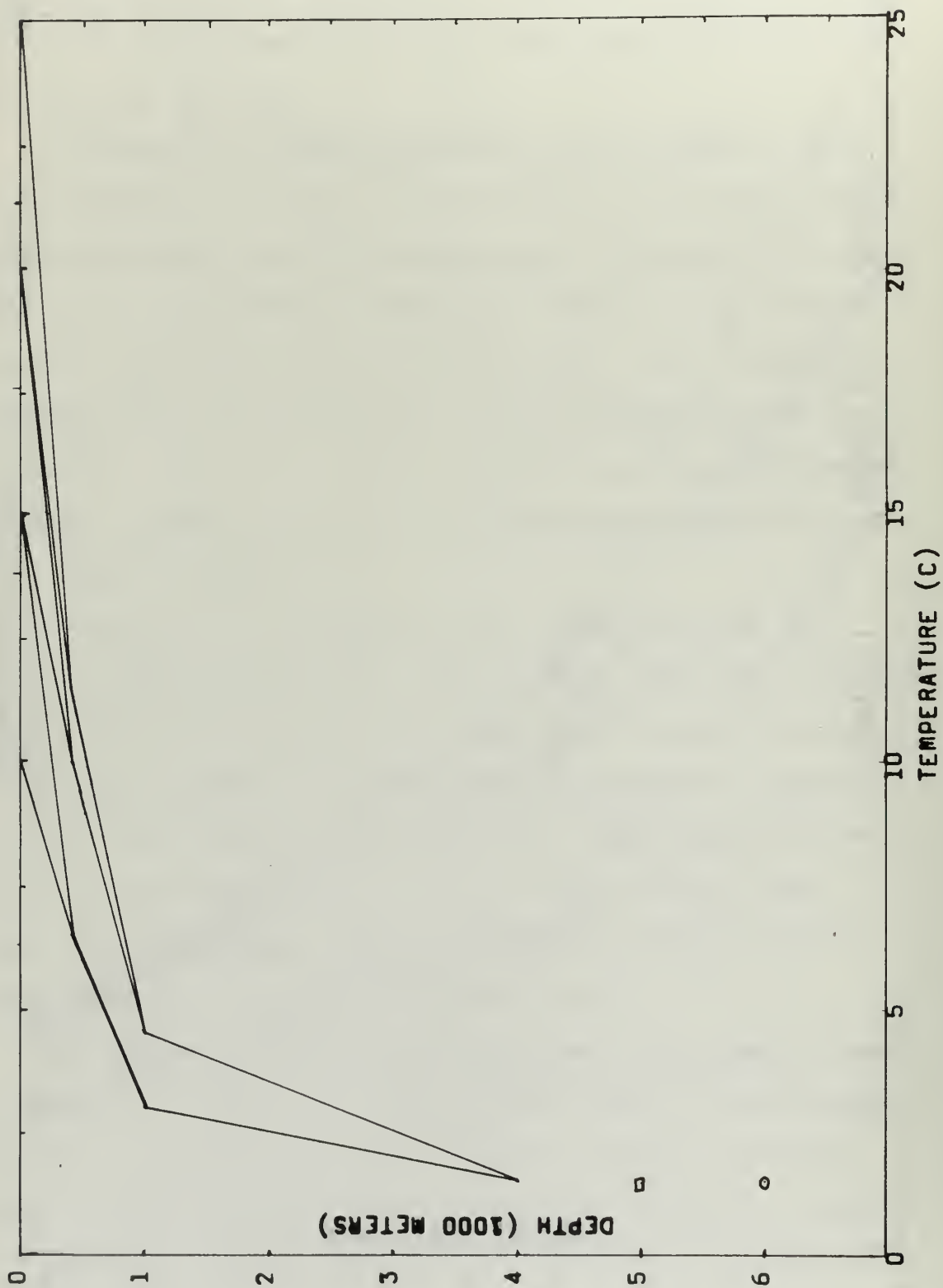
60 feet and mixed layer depth + 100 feet, and the receiver depths
were limited to 90 feet and 300 feet. It was decided that sea state
four would give adequate information for operational use. The output
for each program was thus reduced to four sets of 250 data points.

More thorough analysis of the initial data showed the necessity
for additional refinement; it became obvious that more variation would
be required in sea surface temperature values to obtain meaningful re-
sults. Therefore, intermediate sea surface temperatures and their
associated profiles for 11C, 12C, 13C, 14C, 16C, 17C, 18C, and 19C were
entered into the propagation loss model. No convergence zones appeared
for sea surface temperatures greater than about 18C at 4000-meter
water depth and so additional computer runs were made for depths of
5000 meters and 6000 meters for temperatures from 20 to 25C.

Data were developed for the 100-Hz receiver at 90 feet depth with
a source at 60 feet and at sea state four. These data were examined
closely for information about convergence zone range, width, and inten-
sity for convergence zones one, two, and three. The range to the 100-
decibel propagation loss was also examined.

CHAPTER IV

PROPAGATION LOSS FOR OPERATIONAL USAGE

The formulas and graphical representations of the data were
developed to give the clearest and most concise display for opera-
tional employment. They can be used easily with operator input of sea
surface temperature, mixed layer depth, and water depth.

Convergence Zone Range

The first parameter to be examined was the range to the conver-
gence zones. Preliminary review indicated the most promising avenue
of approach related the convergence zone range to sea surface tempera-
ture and mixed layer depth. Water depth was varied over a sufficient
range to achieve convergence zone development for sea surface tempera-
tures up to 25C.

Data were developed for mixed layer depths of 0 to 300 meters at
100-meter increments for the temperature limits of 10C and 25C. Due to
computer time required for each run and data reduction time, effort was
concentrated on the 100-meter mixed layer depth for temperatures except
10 to 15C where computations were carried out for all four mixed layer
depths and one-degree temperature increments.

Using the data obtained, graphs were plotted covering the tempera-
ture band from 10 to 25C for mixed layer depth of 100 meters and for
all four mixed layer depths from 10 to 15C. A simple equation for
convergence zone range prediction was developed from these data. The
development method is shown in the Appendix. This equation uses the
direct relationship of convergence zone range to sea surface tempera-
ture and mixed layer depth to predict range to the first, second, and
third convergence zones.

$$R = \left[\, 22.70 + 0.55(T - 10)\right]\; Z$$

$$+ \left[(T - 9)\,(0.25Z^{1.32}) - (Z - 1)^{0.8}\,(0.5)\right]\; \frac{M - 100}{300} \qquad (4)$$

where

R = range to the start of the convergence zone (nautical miles)

T = sea surface temperature (degrees C)

Z = convergence zone number

M = mixed layer depth (meters).

The errors produced by the formula are very small compared with the width of the convergence zone (see Tables 4, 5, and 6 in Appendix). The average standard deviation of this equation for convergence zones one, two, and three at mixed layer depth of 100 meters is 0.61 nautical miles. The variance and standard deviation for each of the three convergence zones is given in Table 1.

RANGE PREDICTION ACCURACY

	Variance (NM)	Standard deviation (NM)
ZONE 1	0.608	0.786
ZONE 2	0.234	0.483
ZONE 3	0.314	0.560

TABLE 1

Convergence Zone Width

Width of the convergence zones did not lend itself to any easily-predicted formula or organized tabulation of meaningful results when compared with mixed layer depth or sea surface temperature. The

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greatest pattern appeared to be within each group of convergence
zones. As shown in Table 3, the width of the second convergence zone
was usually about twice the first and the width of the third convergence
zone was about three times the first. The width of the first conver-
gence zone seemed generally to vary between two and four nautical miles;
a few exceptions were as low as one nautical mile and as high as six
nautical miles. The second and third convergence zones followed the
pattern mentioned earlier and were between four and eight nautical miles
and six and twelve nautical miles respectively. The percentage dis-
tribution of these data is given in Table 2, for thirty-six observa-
tions of each convergence zone.

<u>CONVERGENCE ZONE WIDTH</u>

<u>ZONE 1 WIDTH</u> (NM)			<u>MINIMUM</u>	<u>MAXIMUM</u>
2.0-4.0	<2.0	>4.0	1.0	6.0
64.0%	14.0%	22.0%		

<u>ZONE 2 WIDTH</u> (NM)				
4.0-8.0	<4.0	>8.0	1.5	10.5
55.5%	28.0%	16.5%		

<u>ZONE 3 WIDTH</u> (NM)				
6.0-12.0	<6.0	>12.0	2.0	14.0
58.5%	30.5%	11.0%		

TABLE 2

This distribution should enable the operator to make a reasonable
estimate of the zone width.

<u>Convergence Zone Intensity</u>

Convergence zone intensity did not lend inself to direct correla-
tion between mixed layer depth, sea surface temperature, or water depth.

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CONVERGENCE ZONE WIDTH (NM)

DEPTH 4000m	TEMP (C)							
MLD ZONE	10	11	12	13	14	15	16	17
000 1					5.5	4.5		6.0
2					10.0	9.0		10.5
3					14.0	4.5		13.0
100 1		3.0	4.0	2.0	2.0	3.5	1.0	2.0
2		5.0	7.5	3.0	4.0	6.5	2.5	3.5
3		7.0	10.5	4.5	6.0	10.0	2.5	5.5
200 1		5.0	4.0		3.5	4.0	3.0	2.0
2		10.0	8.0		6.5	7.5	6.0	3.0
3		6.0	10.0		9.5	11.0	8.5	4.0
300 1		2.0	3.5	1.0	1.5	3.5		
2		4.0	6.5	1.5	3.0	6.5		
3		6.0	9.5	2.0	4.5	10.0		

DEPTH 5000m	TEMP (C)							
MLD ZONE	10	11	12	13	14	15	16	17
100 1	5.0		3.0				2.5	
2	9.5		5.5				4.5	
3	12.5		8.0				6.0	

DEPTH 6000m	TEMP (C)							
MLD ZONE	10	11	12	13	14	15	16	17
100 1			3.5					
2			6.5					
3			9.5					

DEPTH 5000m	TEMP (C)							
MLD ZONE	18	19	20	21	22	23	24	25
100 1	5.5		2.5	4.0	1.0	1.0	3.5	
2	3.5		5.0	7.0	3.0	1.5	6.5	
3	4.5		6.5	10.5	4.5	2.0	10.0	

DEPTH 6000m	TEMP (C)							
MLD ZONE	18	19	20	21	22	23	24	25
100 1	3.5				2.5	3.0	4.5	6.0
2	6.5				4.5	6.5	8.5	3.0
3	9.5				6.5	9.0	12.5	4.0

TABLE 3

Using Figure 9 the operator in the field can immediately assess his opportunity of obtaining a target with a source level less than 85 decibels, between 85 decibels and 95 decibels, and greater than 95 decibels for each of the first three convergence zones. The break points between various decibel levels were determined for operational usefulness and have no other distinct meaning.

The fact that no easily-formulated relationships could be determined from the data obtained for convergence zone width and intensity does not reduce the importance of the work. It indicates the apparent complexity of the convergence zone width and intensity as related to sea surface temperature, mixed layer depth, and water depth. However, the results obtained are still extremely useful to indicate probability of gaining contact by the operator in the field.

100-Decibel Propagation Loss Level

The last parameter covered is the range to the 100-decibel propagation loss level. This range was chosen as being representative of the capability of a low-frequency passive system.

This range was found to vary with water depth, mixed layer depth, and sea surface temperature. The graphical representation can be seen in Figures 10 and 11 (note change in scale for range between Figure 10 and Figure 11). These figures show the variation of range with sea surface temperature and mixed layer depth and with sea surface temperature and water depth.

The 100-decibel loss range can be determined using the following formula:

$$R_{100} = 13.25 - 0.12 \, \frac{D - 4000}{1000} \, (T - 10) + (I) \text{ or } (II) \qquad (5)$$

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CONVERGENCE ZONE INTENSITY

Figure 9

Figure 10

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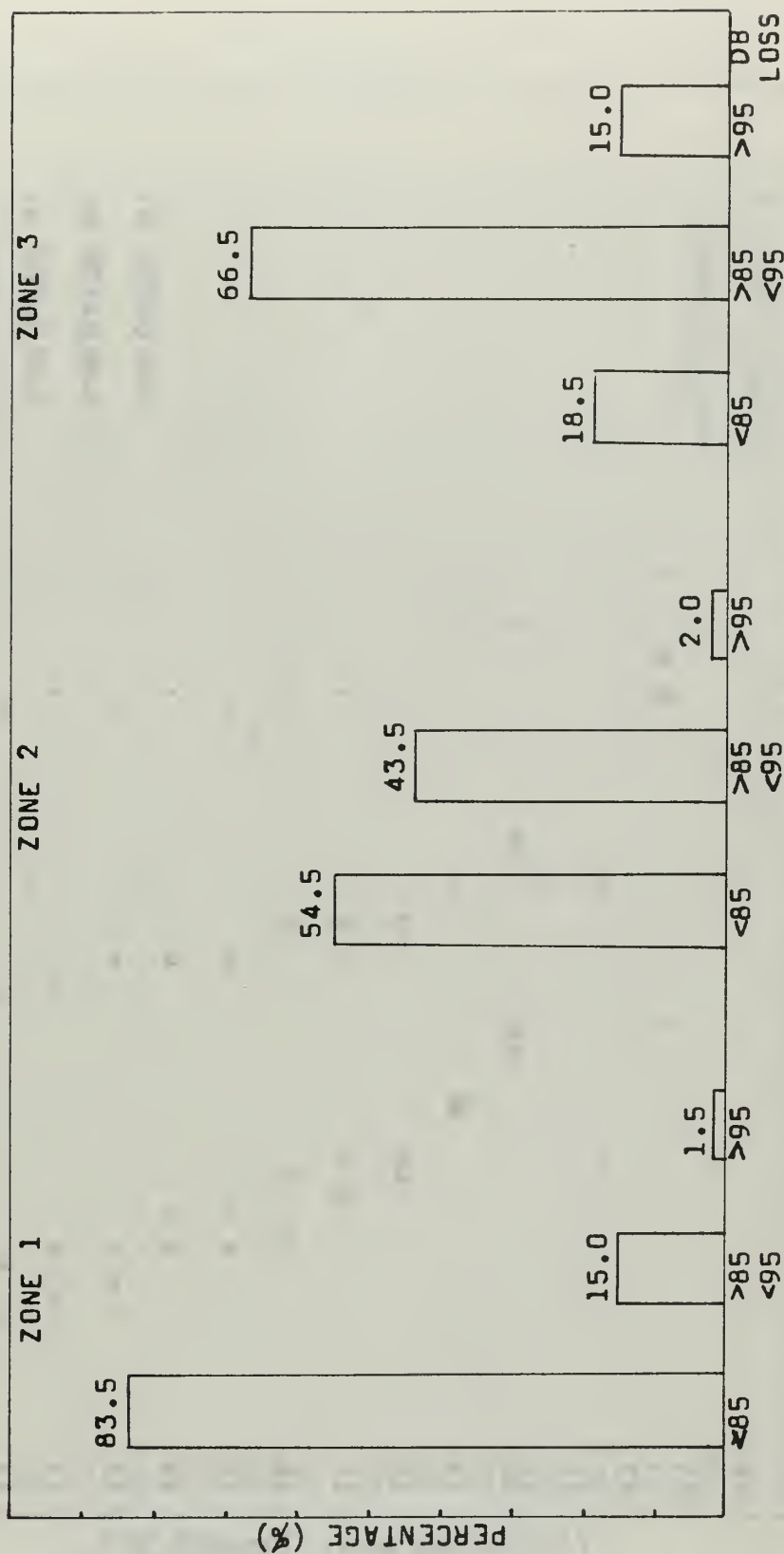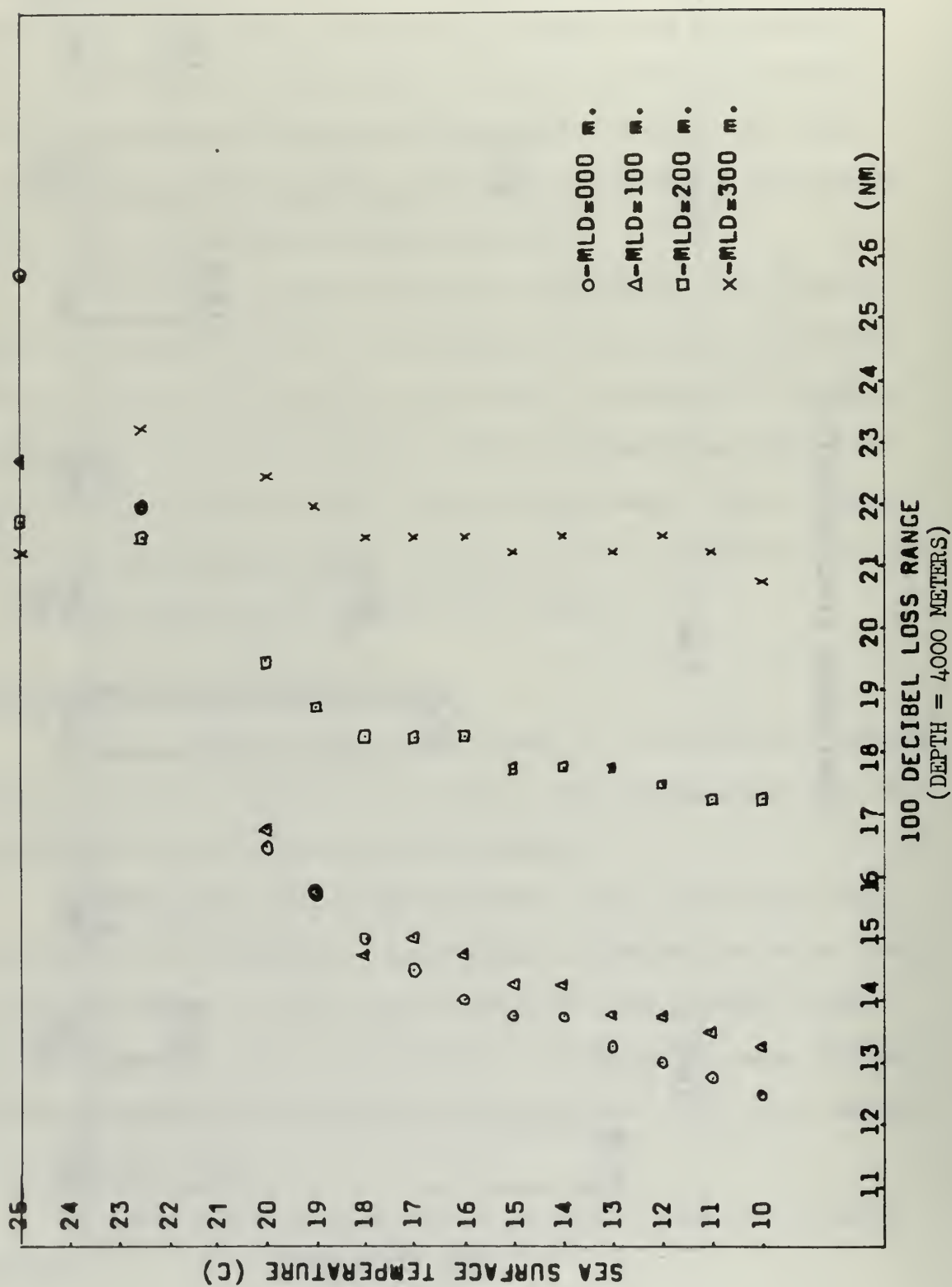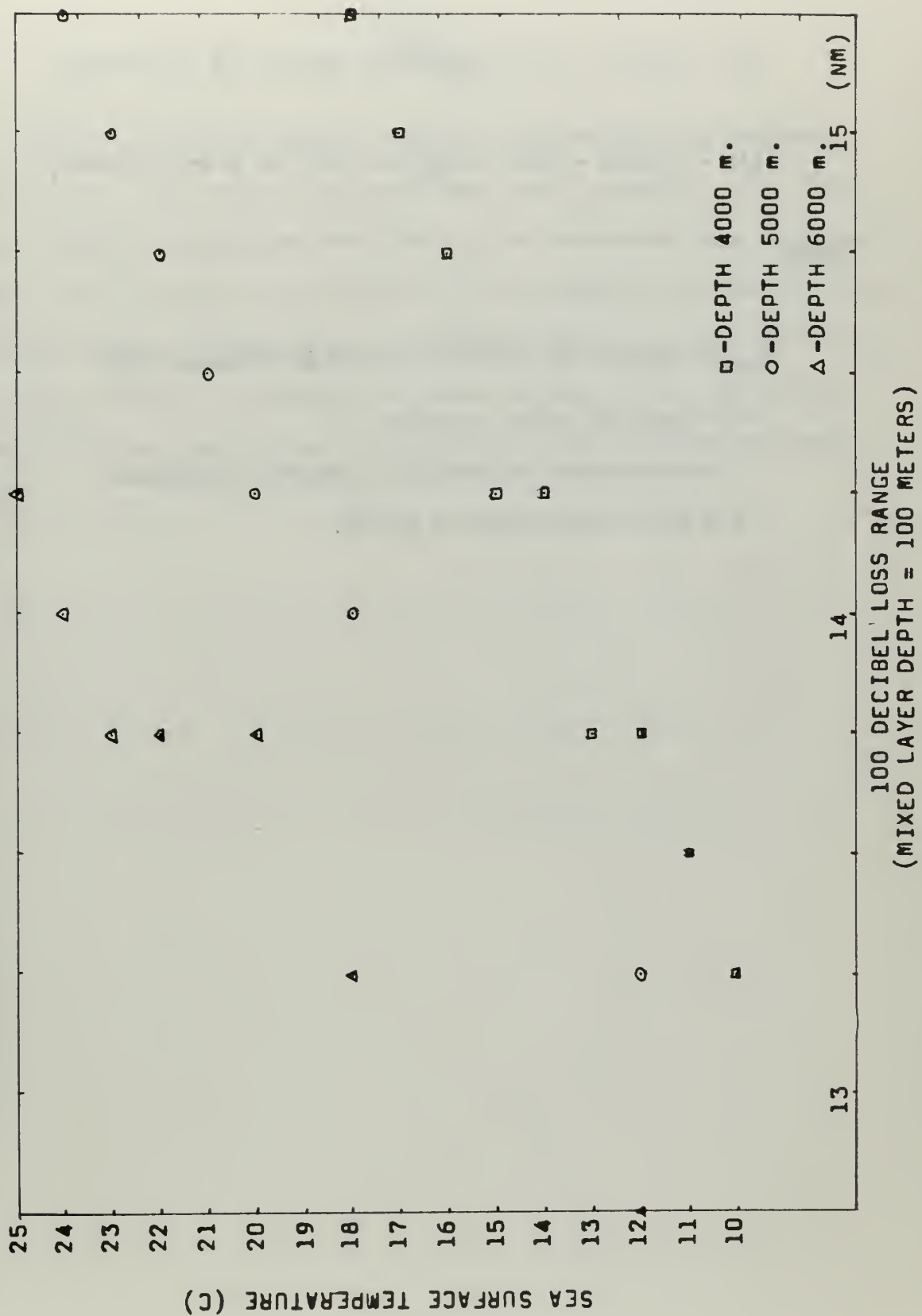
Figure 11

$$(I) = 0.25(T - 10) + \frac{M - 100}{100} (0.75) \text{ for } M \leqslant 100 \text{ meters;}$$

$$(II) = 0.155(T - 10) + \frac{M - 100}{100} (4.00) \text{ for } M > 100 \text{ meters;}$$

where

R_{100} = distance to 100-decibel loss in nautical miles

D = depth of water in meters

T = sea surface temperature in degrees Centigrade

M = mixed layer depth in meters.

CHAPTER V

CONCLUSIONS

Equation (4) was developed to predict the range to the starting
point of the first three convergence zones and is accurate within 1500
yards. Used in conjunction with Table 2 for convergence zone width and
Figure 9 for convergence zone intensity, the operator can establish the
location, width, and intensity of convergence zones one, two, and three.
The field operator can obtain an accurate estimate of the 100-decibel
propagation loss range by use of equation (5) where convergence zones
form.

CHAPTER VI

RECOMMENDATIONS

The convergence zone range should be examined more thoroughly for mixed layer depths between the surface and 100 meters. A more detailed examination over more shallow layer depths should permit refinement of the present formula for greater accuracy.

Convergence zone width and convergence zone intensity should be investigated using a different method than the approach presented in this paper. A constant temperature profile might be maintained and the frequency of the source might be varied over a broad range of frequencies to find a relationship.

The 100-decibel propagation loss range should be investigated using the excess depth below the convergence zone as a reference. More temperature profiles should be processed to refine the prediction formula at mixed layer depths other than 100 meters and for water depths other than 4000 meters.

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APPENDIX

Convergence zone range formula

$$R = \left[22.70 + 0.55(T - 10)\right] \; Z$$

$$+ \left[(T - 9)\,(0.25Z^{1.32}) - (Z - 1)^{0.8}\,(0.5)\right] \; \frac{M - 100}{300}$$

This formula was developed in two parts. The first part related con-
vergence zone range to sea surface temperature at the fixed mixed layer
depth of one hundred meters.

Using the least squares method a first-degree polynomial was
fitted to the data for zone one, zone two, and zone three. The results
of this fit gave the following polynomials:

ZONE 1 $22.70 + 0.55(T - 10)$

ZONE 2 $45.39 + 1.102(T - 10)$

ZONE 3 $68.07 + 1.644(T - 10)$

These three polynomials were then reduced to the polynomial:

$$\left[22.70 + 0.55(T - 10)\right] \; Z$$

T = sea surface temperature in degrees Centigrade

Z = convergence zone number one, two, or three

A plot of the actual data with the least squares curve fitted to
it is given in Figure 12. As sea surface temperature increases it is
necessary to consider deeper water depths in order for a convergence
zone to form.

To develop the second part of the formula the first part was used
as a standard. Then the change was calculated as a positive or

Figure 12

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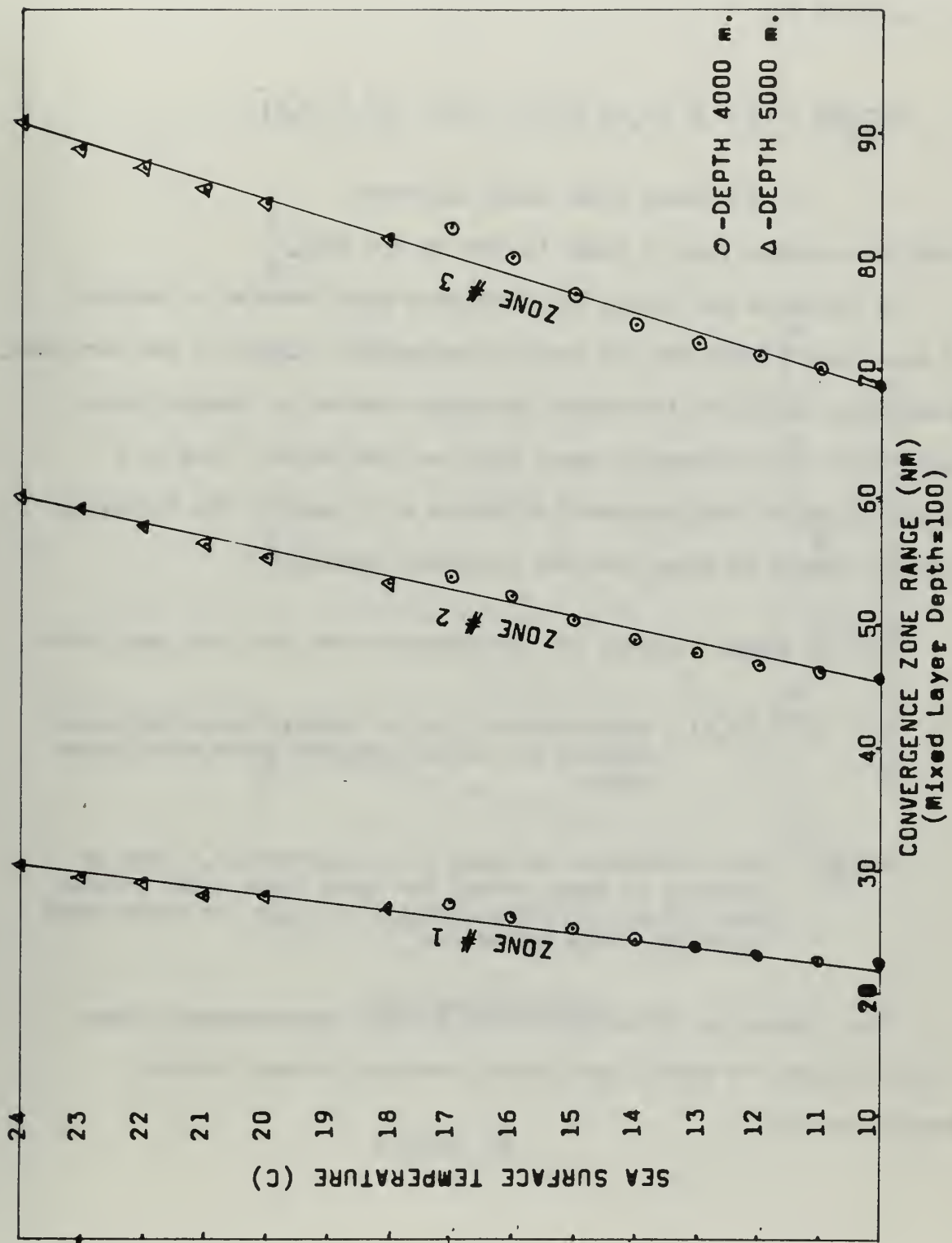
negative range as mixed layer depth increased or decreased from one
hundred meters. This correction for the change in mixed layer depth
is expressed by:

$$\frac{M - 100}{300} \left[(T - 9) \, (0.25 \, Z^{1.32}) - (Z - 1)^{0.8} \, (0.5) \right]$$

M = mixed layer depth in meters

(Note this entire term is equal to zero at M = 100).

To represent the change in convergence zone range as a function
of mixed layer depth and sea surface temperature, Figure 13 was developed.
This figure shows the increasing divergence caused by changing mixed
layer depth for convergence zones one, two, and three. This is a
reduction of the data presented in Tables 4, 5, and 6. The following
features should be noted from the graphical display:

$Z^{1.32}$ – change in slope for convergence zones one, two, and three

$(Z - 1)^{0.8}$ (0.5) – term corrects for the initial range difference
between the surface and 300 meter mixed layer
depth

$\frac{M - 100}{300}$ – term determines the sign of the correction. Thus an
increase in range occurs for mixed layer depth greater
than 100 meters and a decrease in range for mixed layer
depth less than 100 meters.

This formula is effective for sea surface temperatures between
10 and 25C and for mixed layer depths from the surface to three
hundred meters.

Figure 13

PREDICTED AND ACTUAL RANGE OF CONVERGENCE ZONE ONE

P = predicted range (nautical miles)

A = actual range (nautical miles)

T (C)	MLD = 000m		MLD = 100m		MLD = 200m		MLD = 300m	
	P	A	P	A	P	A	P	A
10	22.62	22.50	22.70	23.00	22.78	23.00	22.86	23.00
11	23.08	23.00	23.25	23.00	22.92	23.50	23.59	23.50
12	23.55	23.00	23.80	23.50	24.05	24.00	24.30	24.00
13	24.02	23.50	24.35	24.00	24.68	24.50	25.01	24.50
14	24.48	24.00	24.90	24.50	25.32	25.00	25.74	25.50
15	24.95	24.50	25.45	25.50	25.95	25.50	26.45	26.00
16	25.42		26.00	26.50	26.58		27.16	
17	25.88		26.55	27.50	27.22		27.89	
18	26.35		27.10	27.00	27.85		28.60	
19	26.82		27.65		28.48		29.31	
20	27.28		28.20	28.00	29.12		30.04	
21	27.75		28.75	28.00	29.75		30.75	
22	28.22		29.30	29.00	30.38		31.46	
23	28.68		29.85	29.50	31.02		31.19	
24	29.15		30.40	30.50	31.65		32.90	
25	29.62		30.92		32.33		33.61	

TABLE 4

PREDICTED AND ACTUAL RANGE OF CONVERGENCE ZONE TWO

P = predicted range (nautical miles)

A = actual range (nautical miles)

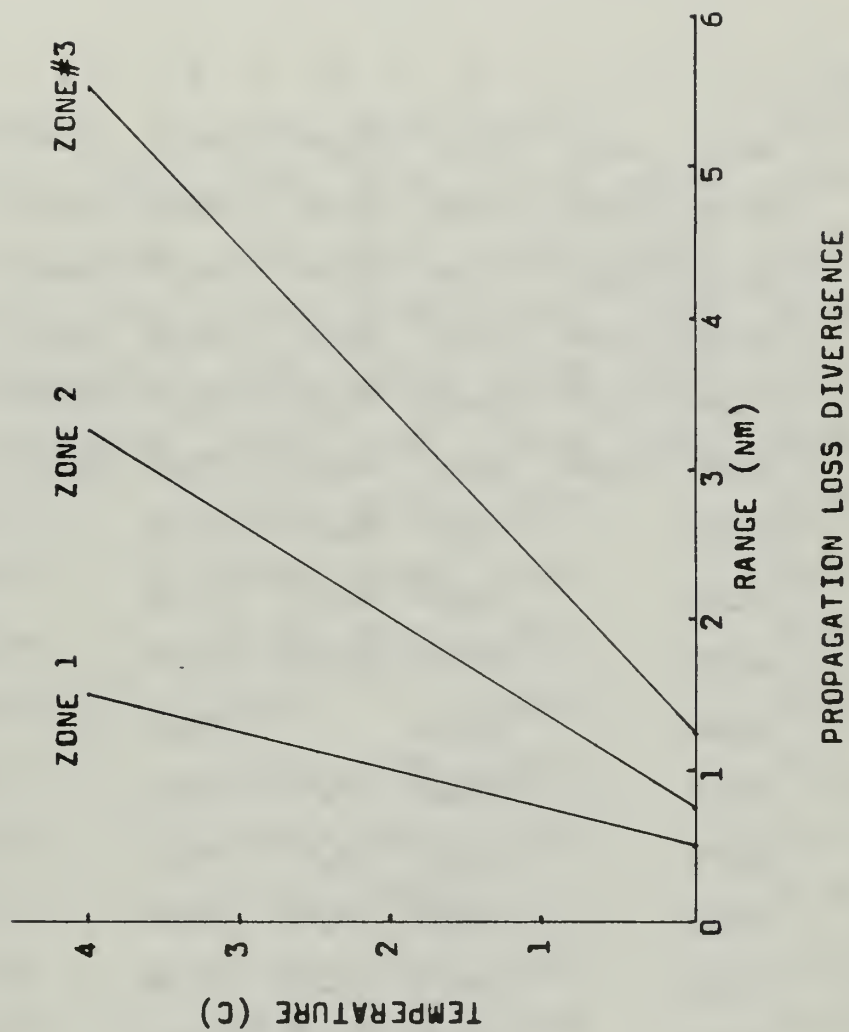|	MLD = 000m		MLD = 100m		MLD = 200m		MLD = 300m	
T (C)	P	A	P	A	P	A	P	A
10	45.36		45.40	46.00	45.44		45.48	
11	46.25	46.00	46.50	46.50	46.75	46.50	47.00	46.50
12	47.14	46.50	47.60	47.00	48.06	48.00	49.52	48.00
13	48.03	47.00	48.70	48.00	49.37	48.50	50.03	49.50
14	48.92	48.00	49.80	49.00	50.58	50.00	51.45	50.50
15	49.82	49.00	50.90	50.50	51.98	51.50	53.06	52.50
16	50.71		52.00	52.50	53.29		54.58	
17	51.60		53.10	54.00	54.60		56.10	
18	52.49		54.20	53.50	55.91		57.62	
19	53.38		55.30		57.22		59.14	
20	54.18		56.40	55.50	58.52		60.64	
21	55.17		57.50	56.50	59.83		62.16	
22	56.06		58.60	58.00	61.14		63.68	
23	56.95		59.70	59.50	62.45		65.20	
24	57.84		60.80	61.00	63.76		66.72	
25	58.73		61.90		65.07		68.24	

TABLE 5

PREDICTED AND ACTUAL RANGE OF CONVERGENCE ZONE THREE

P = predicted range (nautical miles)

A = actual range (nautical miles)

T (C)	MLD = 000m		MLD = 100m		MLD = 200m		MLD = 300m	
	P	A	P	A	P	A	P	A
10	68.04		68.10	68.50	68.16		68.23	
11	69.33	69.00	69.75	70.00	70.17	70.00	70.58	70.00
12	70.63	69.50	71.40	71.00	72.17	72.00	72.91	72.00
13	71.93	70.50	73.05	72.00	74.17	73.00	75.29	74.00
14	73.23	72.00	74.70	73.50	76.17	75.00	77.64	76.00
15	74.52	73.00	76.35	76.00	78.18	78.00	80.01	78.50
16	75.82		78.00	79.00	80.18		82.36	
17	77.11		79.65	81.50	82.19		84.73	
18	78.41		81.30	80.50	84.19		87.08	
19	79.71		82.95		86.19		89.43	
20	81.00		84.60	83.50	88.20		91.80	
21	82.31		86.25	84.50	90.19		94.13	
22	83.60		87.90	87.00	92.20		96.50	
23	84.90		89.55	89.00	94.20		98.85	
24	86.19		91.20	91.50	96.21		101.22	
25	87.49		92.85		98.21		113.57	

TABLE 6

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13. ABSTRACT

This paper reports an attempt to simplify for ease in field use the complex numerical model for sound propagation loss prediction developed by Dr. C. S. Clay, Captain P. M. Wolff, and Dr. P. R. Tatro (LCDR, USN). Due to time required for communications and computation, the present results of this model are not available for immediate use by the operator in the field.

This computerized model was used to analyze propagation loss for temperature profiles with sea surface temperature varying between 10C and 25C and variation in mixed layer depth from the surface to 300 meters. From these data formulas and graphs were developed to predict convergence zone range, width, and intensity and the 100-decibel propagation loss range. These results are intended for operational use by field personnel.

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